VISUALISATION TOOL TO ESTIMATE THE EFFECT OF DESIGN PARAMETERS ON THE HEATING ENERGY DEMAND IN THE EARLY DESIGN PHASES

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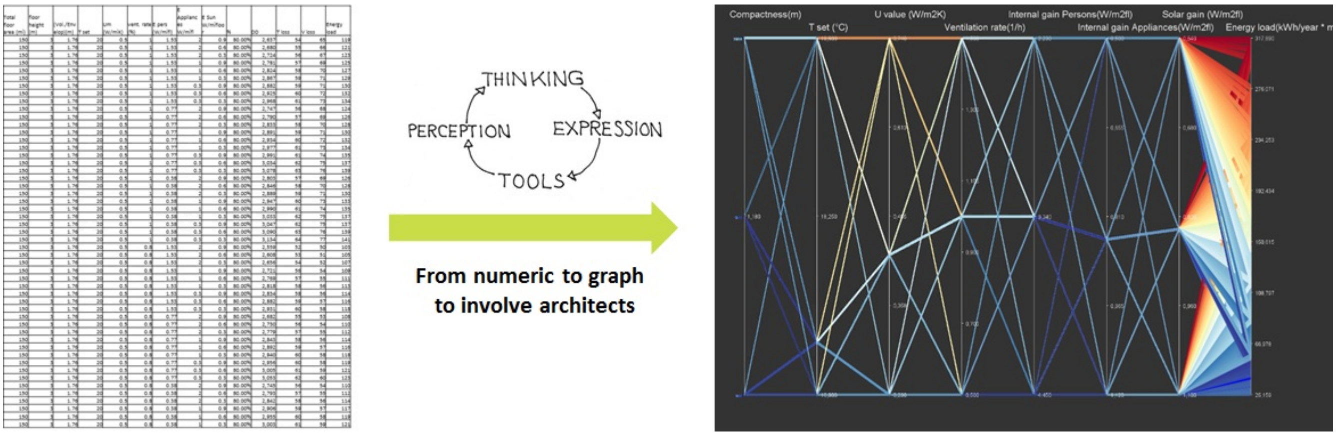

Fig 1: From numerical data to parallel coordinate visualisation

WHICH ARE YOUR ARCHITECTURAL (R)SOLUTIONS TO THE SOCIAL, ENVIRONMENTAL AND ECONOMIC CHALLENGES OF TODAY?

Research summary

To date powerful dynamic simulation tools are available to estimate the energy consumption in buildings. However, these require a lot of input and generate a large amount of output data. This output has to be filtered to select relevant results for early design phases. As a consequence, early design decisions regarding energy efficiency are in practice often based on architects' experience or intuition. As architects think in a graphical way, this paper proposes a tool to visualise the effect of decisions on the heating energy demand, based on the developed "dynamic Equivalent Degree Day method". Using a macro, this tool generates automatically parameter combinations, calculates the energy use and represents results graphically. Relevant sketch design parameters can be manipulated graphically such as the thermal compactness, insulation level, the effective use of direct and indirect solar gains, internal gains including occupant presence and activities, and global ventilation strategies. It is expected that energy demand visualisation can improve the integration of energy efficient design into the architectural process from the sketch design stage onwards. In addition, visualisation is a powerful communication tool for architects to share information and ideas with other architects, engineers, stakeholders and users towards realising Nearly Zero Energy Buildings. The approach is elaborated for the Belgian context, but can be applied to other contexts.

Keywords: *Parametric simulation, dynamic Equivalent Degree Day method, energy performance, early design phases, visualisation tool, occupant behaviour, communication tool*

1. Introduction

The 2010 European Directive on the Energy Performance of Buildings (EPBD) requires EU member states to reduce the energy consumption in new buildings in order to achieve the objective of Nearly Zero Energy Buildings (NZEBs) by 2020 (EPBD recast, 2010).
To date, the majority of Building Performance Simulation tools are post-design evaluative tools (Attia, Gratia, De Herde, & Hensen, 2012) (U.S. Department of Energy, n.d.). These tools are complicated and require expert knowledge from architects (Macris, Weytjens, Geyskens, Knapen, & Verbeeck, 2012). In the most recent decade, tools have been developed to support decisions related to energy efficient buildings in the early design phase, such as jEPlus, DesignBuilder and BeOpt (Attia et al., 2012). A lot of research has been done to integrate energy simulations in the early design phase. However, no current tool attempts to help architects from sketch design stages onwards by representing an extensive parameter study in a graphical way.
In order to reach the EPBD target, architects will be required to include energy efficiency in the design process, especially in small scale projects with a lack of engineers' support due to financial and time constraints. Hence, the objective of this study is to improve the integration of energy simulations for architects by using a visualisation tool in the early stages of the design process.
Gänshirt proposed the concept of the design cycle, which describes the reflective and repetitive structure of architectural design processes (Figure 2) (Gänshirt, 2007). In a constant feedback loop, architects use visual and verbal tools to communicate their ideas (Anderson, 2011). In architectural design, visual tools are considered as more important than verbal ones in architectural design. In other areas, like engineering, the use of verbal tools including numerical datasets, are prevalent (Gänshirt, 2007). Therefore the visualisation of numerical data is a powerful tool to communicate with and assist architects.

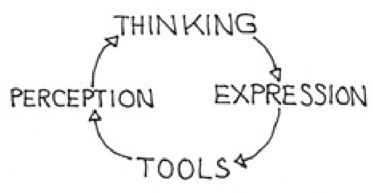

Fig 2: Design process diagram (Gänshirt, 2007)

2. Description of the tool for heating energy demand estimation

2.1 The basic possibilities of parallel coordinates
In a 3D representation one can represent how two variables affect an output function. Parallel coordinates (Inselberg & Dimsdale, 1990) allow representing how a whole range of variables affects one (or even more) output functions. Input and output are represented on parallel axes. All input values leading to one (or more) output results are connected via a line (Figure 3) The representation becomes more powerful when several combinations are represented on one graph. Depending on the result (in this case the heating energy demand per m² floor area) a colour gradient can be generated (Figure 4). Several software tools are available to edit the graphical representation. For this paper "Xdat version 2.2" (*Xdat version 2.2*, 2015) is used.
Editing operations are (Figure 5):

- Changing the order from left to right of the coordinate lines

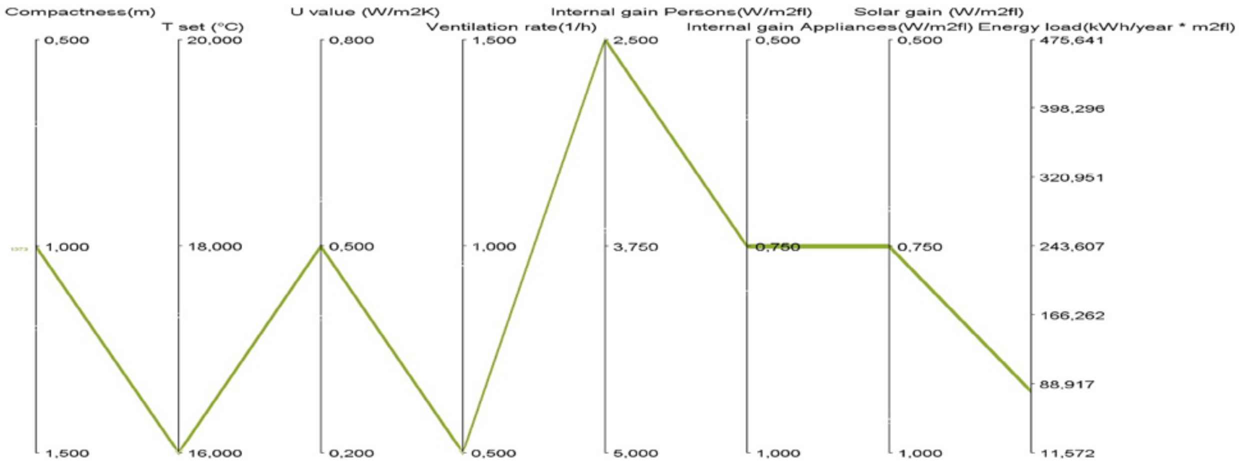

Fig 3: One combination of input parameters and output results in a parallel coordinate visualisation

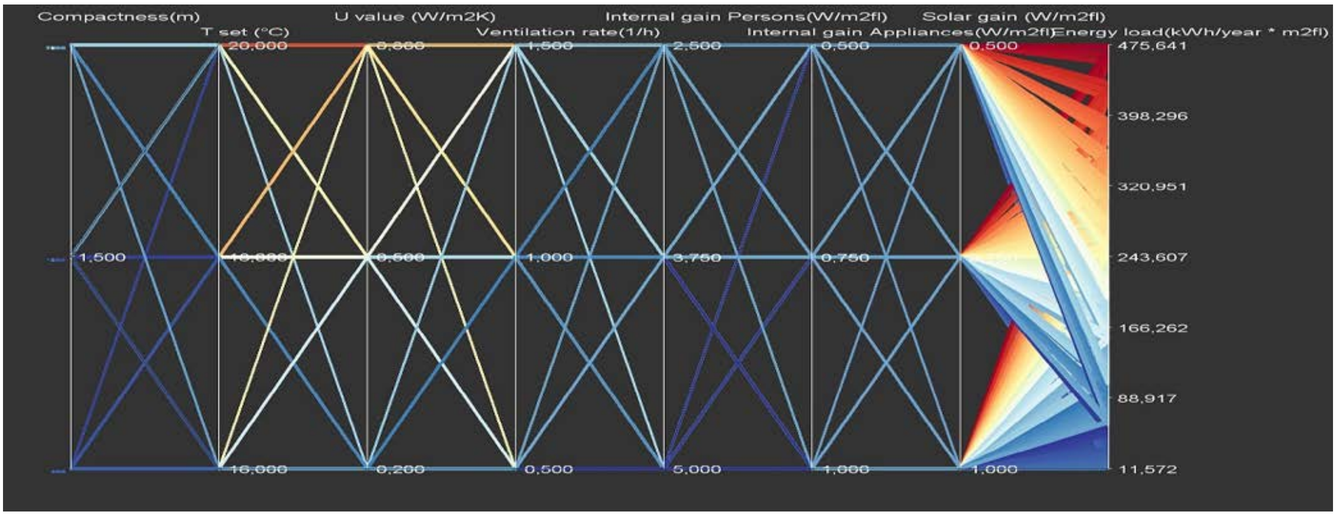

Fig 4: Overview of combinations in a N-dimensional parallel coordinate visualisation

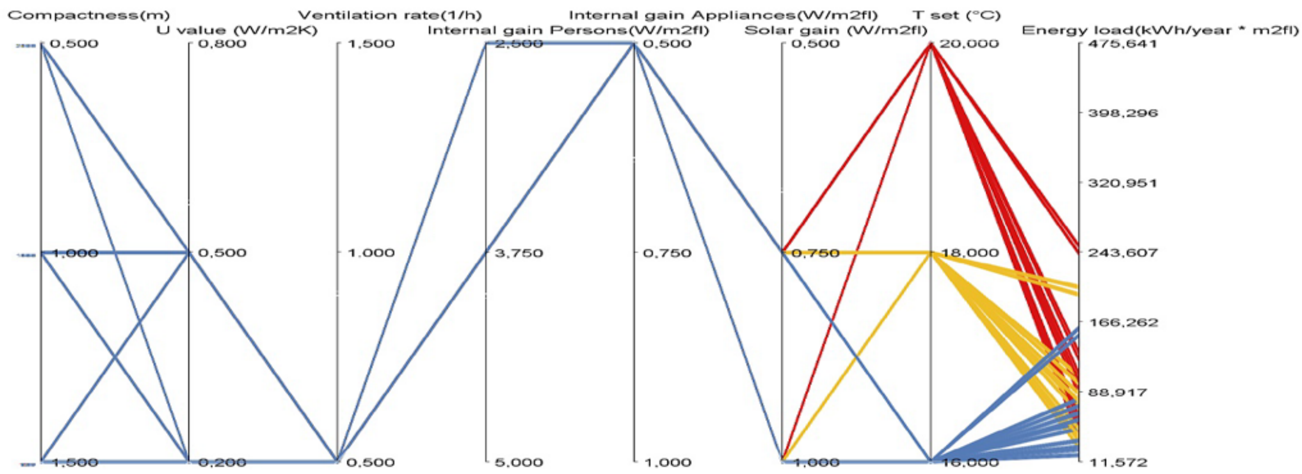

Fig 5: Reference of parallel coordinate functions

Table 1: Input parameters, variable range and steps of values

No.	Parameter	minimum	maximum	steps
1	Compactness (Vol./Envelop) (m)	0.5	1.5	2
2	Average Setpoint Temperature (C°)	16	20	2
3	Average U value (W/m^{2}K)	0.2	0.8	2
4	Ventilation rate (1/h)	0.5	1.5	2
5	Internal gain by people (W/m^{2}fl)	2.5	5	2
6	Internal gain by appliances (W/m^{2}fl)	0.5	1	2
7	Solar gain (W/m^{2}fl)	0.5	1	2

- Changing the minimum and the maximum of each coordinate
- Inverting the axis direction
- Reducing or increasing the distance between parallel lines for better visualisation
- Applying colour gradient (for instance, from red for higher energy use to blue for lower energy use) (Figure 4)
- Filtering lines by only considering cases where one or several parameters are in between selected minimum and maximum values. Each created set can be represented in a selected colour for further analysis

2.2 The representation of a design space via parallel coordinates

A macro is developed in Excel to generate all possible combinations based on the following data for each input parameter: the minimum value, the maximum value and the number of steps. An example is given in Table 1**.** In this table three values (2 steps) are selected for each input parameter: minimum, average and maximum. Seven parameters and three values for each parameter already lead to 3^7=2187 combinations. The number of combinations is calculated in the spreadsheet based on the input ranges, so that via a step by step approach the number of combinations can be kept manageable. The remaining issue is to calculate the energy use via a fast estimation method, but reliable enough for the first design phases. This method is described in the subsequent section.

2.3 From the Heating Degree Day (HDD) method to the dynamic Equivalent Heating Degree Day (dynamic EHDD) method

The Heating Degree Day (HDD) is a calculation method for predicting the energy demand to heat a building at a specific location. The number of 'Heating Degree Days (HDDs)' is equal to the sum over the whole heating season of the daily temperature difference between the daily average indoor temperature (T_{set}) and the daily average outdoor temperature (T_e). T_{set} depends on the heating setpoint over 24 hours and over all the zones in the building. Figure 6 illustrates the DD 15/18 for the Belgian temperate climate. It is assumed that the heating season starts when the daily average external temperature is lower than 15°C. The space and time average indoor temperature is 18°C. In practice, monthly average outdoor temperatures are used for approximating the number of HDDs, as illustrated by the hatched area in Figure 6.

The Equivalent Heating Degree Day (EHDD) method is a refinement of the HDD method. Compared to the original method, the EHDD method considers the impact of internal gains (resulting from people and appliances) and solar gains, leading to a reduction of the heating energy demand (Ehringer & Zito, 2013). The EHDDs are calculated based on the difference between the temperature curve without heating (T_{WH}) and the temperature line of no more heating (T_{NH}) (Figure 7) (Diensten voor de programmatie van het wetenschapsbeleid, 1984b). The temperature curve without heating (T_{WH}) is defined as the increased indoor temperature resulting from solar gains when the building is without heating and internal gains. The T_{NH} line indicates how far the outdoor temperature can drop below the desired indoor temperature so that the gains can heat the building up to T_{set}, T_{WH} and T_{NH} depend on the thermal insulation level and the ventilation and infiltration rate. The lower the energy losses are, the more the EHDDs can be reduced for the same amount of heat gains (represented by the left over hatched area in Figure 7).

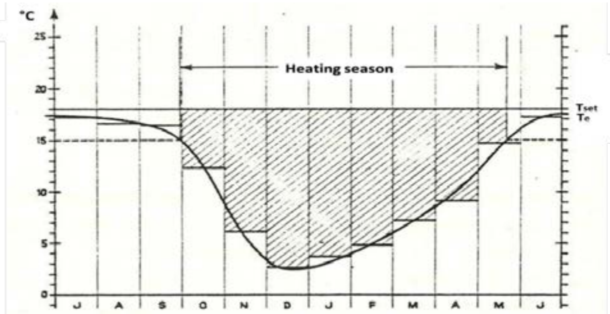

Fig 6: HDD 15/18 for the temperate climate in Belgium (Diensten voor de programmatie van het wetenschapsbeleid, 1984a)

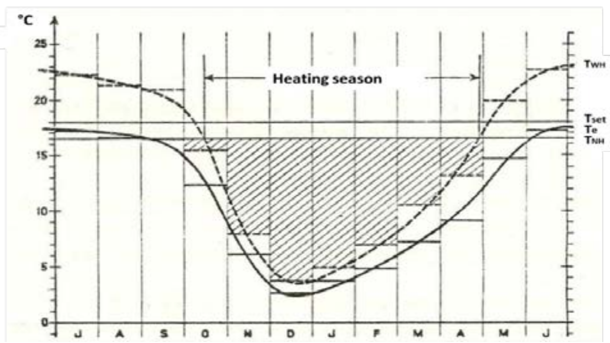

Fig 7: EHDD 15/18 for the temperate climate in Belgium (Diensten voor de programmatie van het wetenschapsbeleid, 1984b)

A recent research, (Trigaux et al., 2014) proposed the dynamic Equivalent Degree Day (dynamic EDD) method, by including more dynamic solar gain calculations, to improve the estimation of the impact of shading obstructions in dense building environments.

In this paper, the dynamic EHDD is developed. First, the outdoor temperature curve is approximated by four lines in order to simplify the calculation process: a linear drop of the outdoor temperature from summer to winter, constant in winter, linear rise from winter to summer, and constant in summer (Figure 8). Since focused on heating energy demand in Belgian context, the dynamic EHDD method considers only spring, autumn and winter periods in this research. Those lines are obtained via linear regression of monthly temperatures reported in the Test Reference Year (Test Reference Year weather data, n.d.) Secondly, these total internal and solar "free" heat gains are translated to an average heat gain rate and can generate temperature increase (ΔT) depending on the transmission and ventilation heat losses by using equation (1),

$$\Delta T = Q_g / (E*U_m + V*n*\beta*\rho*C_p / 3600) \qquad (1)$$

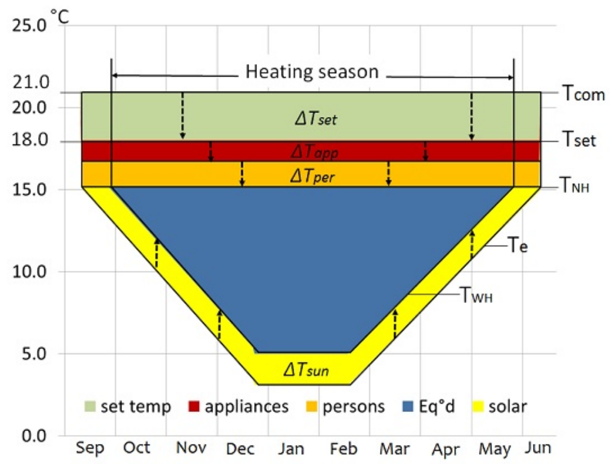

Fig 8: Representation of dynamic EHDD 15/18 for the temperate climate in Belgium

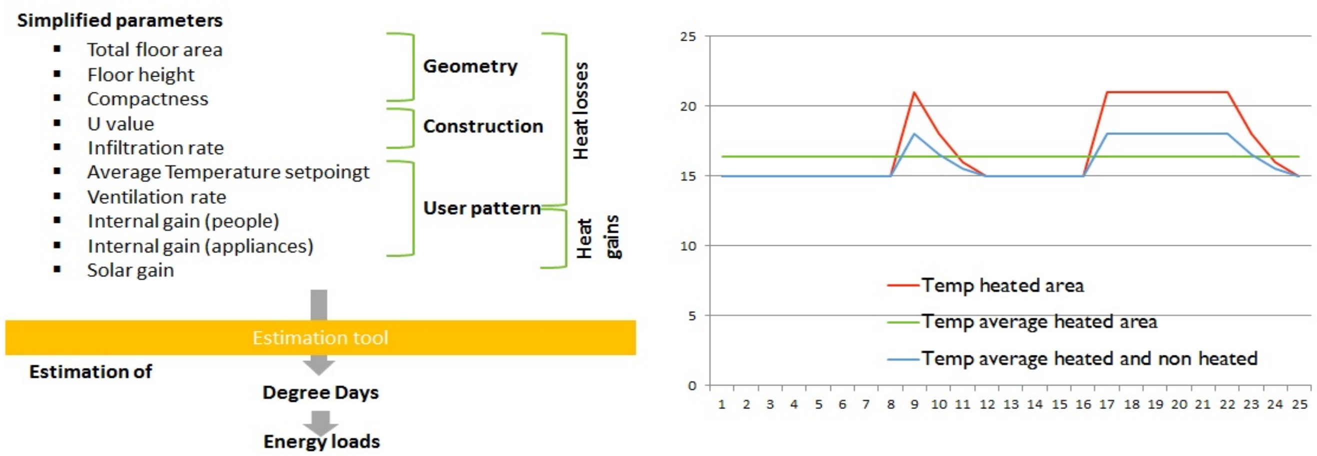

Fig 9: Simplified parameters (left) and representation of user behaviour, setpoint temperature (right)

total floor area (m²)	height (m)	compactness (Vol./Envelop)(m)	Tset (°C)	U-value (W/m²K)	ventilation (1/h)	people (W/m²fl)	appliance (W/m²fl)	solar gain (W/m²fl)	η system (%)	degree day	transmission loss	ventilation loss	energy load	cost €/ (year m²fl)
add case		3	21	2	2	3	6	5	95%	4000	kWh/(year * m² floor)			
120	3.0	1.00	16.5	0.20	0.50	4.60	0.85	1.10	80.0%	914	13	11	24	2.41
120	3.0	1.00	16.5	0.20	0.50	2.30	0.85	1.10	80.0%	1,346	19	17	36	3.55
120	3.0	1.00	16.5	0.30	0.50	2.30	0.85	1.10	80.0%	1,537	33	19	52	5.15
120	3.0	1.00	17.0	0.30	0.50	2.30	0.85	1.10	80.0%	1,661	36	20	56	5.56
120	3.0	0.80	17.0	0.30	0.50	2.30	0.85	1.10	80.0%	1,766	48	22	69	6.86
		0.5	13	0.15	0.05	0.5	0.3	0.3	50%	200				

Fig 10: Dashboard as tool interface

With:

- Q_g = heat gain rate (J/s)
- E= envelop surface (m^2)
- U_m= average heat transfer coefficient (W/m^2K)
- V= building volume (m^3)
- n= air change per hour (1/h)
- β= volumetric coefficient (0.95 m^3/m^3)
- ρ= density of air (1.29 kg/m^3)
- C_p= specific heat capacity of air (1006 J/kgK)

The dynamic EHDDs are represented by the blue area in Figure 8. This approximation is fast and accurate enough to predict the required heating energy and to generate the representation of the design space.

2.4 The "Dashboard" to navigate in the design space

A simple spreadsheet interface, called the "Dashboard", is implemented to input different design options (Figure 10). Annual heating energy demand (Q_E) is calculated by the sum of heat losses by transmission(H_t) and ventilation(H_v) (Equation (2)(3)(4)).

$$Q_E = H_t + H_v \quad (2)$$

$$H_t = E*U_m*dEHDDs*24*3600 / 3600000*A_f \quad (3)$$

$$H_v=V*n*\beta*\rho*C_p *dEHDDs*24 / 3600000*A_f \quad (4)$$

With

- Q_E : annual energy demand (kWh/(year*m^2floor))
- H_t : annual transmission heat loss (kWh/(year*m^2floor))

- H_v : annual ventilation heat loss (kWh/(year*m^2floor))
- dEHDDs : annual dynamic heating Equivalent Degree Days (K*d/year)
- A_f : floor area (m^2)

After a first exploration of the "design space" by parallel coordinates, a set of design options can be generated in order to visualise the different steps in a design process by using the Dashboard. A start proposal can be visualised as one line on the parallel coordinate visualisation and the effect of changing one or several parameters can be represented by additional lines.
Figure 11 illustrates two changes of parameters. First step is the change of the U-value (blue line). The second step is the change of the heating setpoint (green line). The second step is due to the change of the heating pattern in the heating zone and the non-heating zone (Figure 9 right).
An additional spreadsheet tool is developed to support the following functions:

- Changing basic geometry (number of stories, height of each stories, square or rectangular shape of each stories)
- Selecting other type of elements and resulting U values
- Redefining the user schedule for heating
- Calculating heat gains from appliances and occupants
- Defining ventilation strategies and user activities

This approach is elaborated to improve the communication between different stakeholders (architects, engineers and users) and to support architects in their feedback loop of the design process (Figure 2).

3. Conclusions

The proposed approach based on parallel coordinate visualisation consists of two parts. The First part demonstrates that it is possible for architects to have an overview of the "design space" (*top-down approach*). In the second part it is shown that the step by step approach helps architects to grasp the effects of changing design parameters on the heating energy demand (*bottom-up approach*). The combination use of these two approached are efficient for finding design solutions from the early design stage. Architects often hesitate to deal with sets of numerical data. Visualisation is hence a powerful approach to translate the

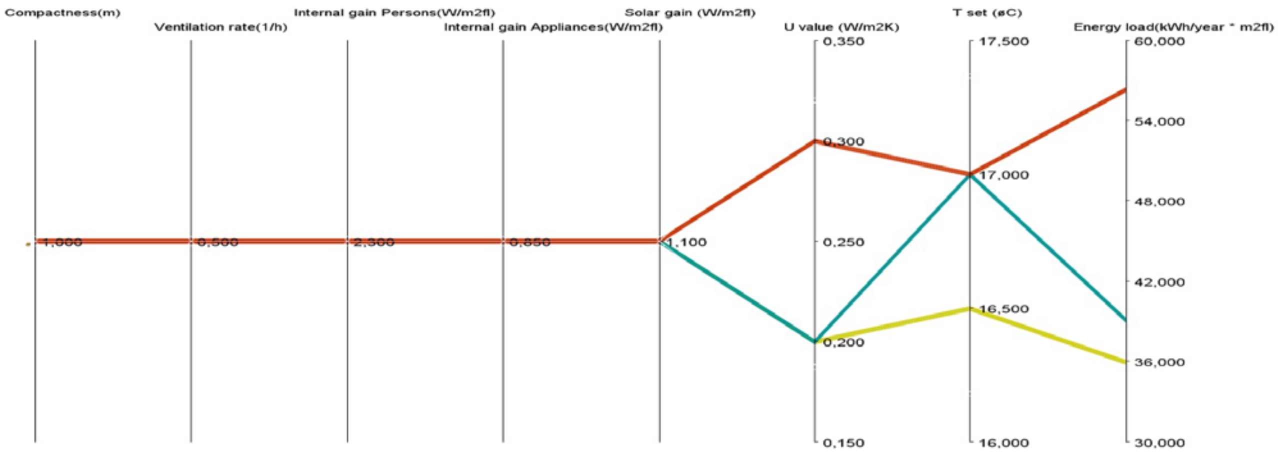

Fig 11: Illustration of design steps

engineer's language (numerical data) into the architect's language (visual representations). Such approach can speed up the analysis of the impact of parameters and the simulation results and improve the integration of energy simulations in the early stages of the design process. The approach increases the insight about the effect of each parameter and the interaction between parameters.

The strength of this approach is its capacity to combine the easy comprehensible visualisation and the fast and comparative estimation with considering occupant behaviours from the sketch design on. Consequently the approach facilitates the architect's design work for energy efficiency and communication with other stakeholders in his/her design process. Moreover, this research can be applied to other contexts for the heating energy demand by using the dynamic EHDD method.

This research is a starting point to assist architects in making decisions for NZEBs from the sketch design stage onwards. For better usability, the spreadsheet tool can include more detailed support sheets to input uncertain decisions. To be used in the detailed design phase, this approach should be extended to more detailed energy calculations. In further research, a link to dynamic energy simulations will be developed.

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